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AI-based pain assessment in physiotherapy: A multidimensional approach to clinical innovation

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Abstract
Artificial Intelligence (AI) is revolutionizing pain assessment in physiotherapy by introducing novel, multidimensional approaches that enhance the accuracy, objectivity, and effectiveness of pain management strategies. Traditional subjective pain scales often fall short in capturing the complex nature of pain, particularly in vulnerable populations. AI-driven pain assessment tools, which leverage wearable sensors and advanced algorithms, provide a promising solution to these limitations. By continuously analysing physiological signals such as photoplethysmography, electrodermal activity, skin temperature, and accelerometer data, AI algorithms can objectively quantify pain and potentially differentiate between nociceptive and neuropathic pain types. This approach enables real-time, non-invasive monitoring during physiotherapy sessions, empowering clinicians to tailor treatments effectively. Moreover, AI-based pain assessment extends beyond physiological data to encompass biopsychosocial factors, aligning with the superior effectiveness of multidimensional physiotherapy interventions in chronic pain conditions. Techniques like EEG spectrum analysis and network analyses further elucidate the interrelationships between pain intensity, disability, and psychosocial functioning, guiding personalized rehabilitation targets. The integration of AI in physiotherapy pain assessment represents a cutting-edge clinical innovation that promises to revolutionize precision medicine strategies by combining continuous wearable sensor data analysis with biopsychosocial evaluation, ultimately improving diagnostic accuracy and therapeutic outcomes in the complex realm of pain management.

Keywords: Artificial intelligence, pain assessment, physiotherapy, machine learning, rehabilitation, wearable sensors, computer vision

Introduction

Pain, a complex, multidimensional experience, plays a critical role in physiotherapy assessment and management. Accurate evaluation of pain intensity and patterns guides clinical decision-making and determines rehabilitation progress. Conventional methods, such as the Visual Analog Scale (VAS), Numeric Rating Scale (NRS), and McGill Pain Questionnaire, are subjective and may be influenced by communication barriers, cognitive impairments, and individual pain thresholds [1].

AI-based pain assessment in physiotherapy represents a cutting-edge clinical innovation that leverages multidimensional approaches to enhance the accuracy, objectivity, and effectiveness of pain management strategies. Pain assessment traditionally relies on subjective patient reports, which are vulnerable to bias and influenced by emotional or cognitive factors [2]. To address these limitations, the integration of wearable sensors and artificial intelligence (AI) has emerged as a promising solution. Specifically, AI algorithms can analyze physiological signals collected continuously via wearable devices such as photoplethysmography, electrodermal activity, skin temperature, and accelerometer data to objectively quantify pain and potentially differentiate between nociceptive and neuropathic pain types. This approach facilitates real-time, non-invasive monitoring during physiotherapy sessions, providing clinicians with actionable insights to tailor treatments effectively [3].

The multidimensional nature of this methodology encompasses not only physiological data but also biopsychosocial factors. For instance, in chronic pain conditions like nonspecific low back pain, multidimensional physiotherapy interventions based on biopsychosocial models have demonstrated superior effectiveness compared to usual care. These approaches consider psychological and social aspects alongside physical symptoms, and advanced methods such as electroencephalography (EEG) spectrum analysis help in understanding brain function alterations related to pain, enhancing treatment personalization. [4] Further, network analyses of chronic low back pain patients reveal that pain intensity and disability are interrelated with psychosocial functioning and perceived physical functionality rather than demographic factors like age or BMI. This insight underscores the need for multidimensional assessment tools that combine AI-driven physiological monitoring with clinical evaluation of psychosocial variables to optimize rehabilitation targets in physiotherapy [5].

Overall, AI-based pain assessment, grounded in a multidimensional framework, promises to revolutionize physiotherapy by enhancing precision medicine strategies. It allows continuous, objective pain quantification, supports differentiation of pain types, and guides personalized treatment interventions that address the complex interplay of physiological, psychological, and social factors in pain management. Therefore, the clinical innovation offered by AI in physiotherapy pain assessment manifests as an integrated, multidimensional approach that improves diagnostic accuracy and therapeutic outcomes by combining continuous wearable sensor data analysis with biopsychosocial evaluation [6].

Methodology

This narrative review is based on a comprehensive literature search performed across major academic databases, including PubMed, Google Scholar, and Scopus. The search employed key terms such as "AI in pain assessment," "physiotherapy," "machine learning in rehabilitation," "wearable sensors," and "computer vision in healthcare." Articles were selected according to their relevance, focus on recent technological developments, and practical applicability in clinical physiotherapy practice.

Technological Foundations of AI-Based Pain Assessment

Artificial Intelligence (AI) has revolutionized pain assessment in physiotherapy by providing objective, real-time insights where traditional self-reporting falls short [7]. Key technologies driving AI-based pain evaluation include:

1. Facial Recognition Algorithms

Utilizing computer vision and machine learning, facial recognition detects subtle pain-related expressions like brow furrowing and grimacing. Clinically validated tools such as PainChek and Face Reader assist in assessing non-verbal patients, especially in neurorehabilitation, paediatrics, and geriatrics [6].

2. Wearable Sensors

Embedded accelerometers, gyroscopes, and electromyography sensors track movement and muscle activity during therapy. AI analyses these data to identify pain-linked compensatory movements, aiding musculoskeletal and neurological rehabilitation [7].

3. Voice Analysis

AI evaluates vocal cues-pitch, tone, hesitation to detect pain and distress, offering a valuable non-invasive tool for remote and tele-rehabilitation settings.

4. Thermal and Infrared Imaging

Infrared cameras capture heat patterns indicative of inflammation or injury. AI interprets these thermal signatures to identify musculoskeletal or neuropathic pain, supporting assessment in sports and orthopaedic physiotherapy.

5. EEG and ECG Integration

Brainwave (EEG) and heart rate variability (ECG) monitoring reveal physiological responses to pain. AI-driven analysis of these signals enhances understanding of chronic pain and guides neurofeedback and biofeedback therapies [8].

Together, these technologies form a multidimensional AI framework that elevates pain assessment accuracy, enabling personalized and effective physiotherapy care.

Applications across Physiotherapy Specialties

AI technologies are transforming pain assessment and management across various physiotherapy specialties by providing objective, real-time data that enhance clinical decision-making and personalize rehabilitation.

Musculoskeletal Physiotherapy: AI employs motion capture, wearable sensors, and biofeedback to quantify pain-related movement dysfunction, analyze biomechanical stressors, and monitor rehabilitation progress in conditions like low back pain and osteoarthritis [7].

Neurological Physiotherapy: For patients with impaired communication, AI analyses facial micro-expressions, movement patterns, EEG signals, and speech changes to detect pain, enabling early intervention and tailored therapy in stroke, Parkinson's disease, and spinal cord injury.

Paediatric Physiotherapy: AI assesses non-verbal pain indicators through cry analysis, facial expression monitoring, and behavioural tracking, improving pain detection and individualized care in infants and children with developmental or neuromuscular disorders.

Cardiothoracic Physiotherapy: AI monitors respiratory patterns, facial and postural cues, heart rate variability, and vocal signals to identify pain affecting breathing and recovery post-surgery or in chronic respiratory diseases, supporting timely interventions.

Obstetrics and Gynaecology Physiotherapy: AI enhances pelvic floor function assessment using wearable sensors, motion analysis, biofeedback, and emotional state detection, optimizing pain management during pregnancy, postpartum, and pelvic disorders.

Oncology Rehabilitation and Lymphedema Management: AI integrates facial and voice analysis, wearable sensor data, and thermal imaging to objectively monitor cancer-related pain and lymphedema, facilitating early detection and personalized rehabilitation.

Geriatric Physiotherapy: AI detects pain in cognitively impaired elderly through facial recognition, behavioural monitoring, motion tracking, and sleep analysis, promoting early intervention, fall prevention, and safer rehabilitation.

Sports Physiotherapy: AI-driven biomechanical analysis, load monitoring, injury risk prediction, and return-to-play decision support enable precise pain assessment, enhancing recovery and reducing reinjury risk in athletes.

Overall, AI's multidimensional approach across these specialties improves diagnostic accuracy, individualizes treatment, and enhances patient outcomes in physiotherapy.

Benefits of AI-Based Pain Assessment

The integration of Artificial Intelligence (AI) in physiotherapy revolutionizes pain identification, quantification, and management by overcoming the limitations of traditional subjective assessments. AI leverages real-time data from sensors, imaging, and behavioural cues to provide objective, adaptive, and predictive pain evaluation models [9]. Key benefits include:

1. Enhanced Objectivity

AI reduces reliance on subjective patient reports by analysing quantifiable data such as facial micro-expressions, vocal patterns, gait, heart rate variability, and electromyography. Tools like PainChek and FaceReader enable standardized, reproducible pain assessments, even in non-verbal or cognitively impaired patients.

2. High Precision and Continuous Monitoring
Unlike intermittent manual assessments, AI enables continuous, real-time tracking of physiological and biomechanical indicators via wearable sensors. This allows detection of subtle pain fluctuations during therapy, facilitating immediate adjustments to treatment for safer and more effective rehabilitation.

3. Personalized and Adaptive Therapy
Machine learning models process individual patient data to create dynamic, personalized pain profiles. AI tailors rehabilitation protocols based on evolving symptoms and functional responses, enhancing treatment efficacy, patient satisfaction, and adherence.

4. Communication Support for Vulnerable Populations
AI bridges communication gaps in non-verbal groups such as infants, neurological patients, and cognitively impaired elderly by interpreting facial expressions, vocal tone, posture, and physiological signals. This ensures timely pain detection and intervention when self-reporting is not possible.

5. Predictive Value and Early Risk Detection
By analysing large datasets, AI identifies patterns predictive of pain chronicity, flare-ups, or treatment response. Early risk detection enables proactive intervention, reducing long-term disability and improving outcomes.

6. Integration with Telehealth and Remote Monitoring
AI supports remote physiotherapy by integrating wearable devices, mobile apps, and cloud platforms to monitor pain continuously outside clinical settings. This facilitates proactive care, especially for patients in remote areas or with mobility limitations [10].

Challenges and Limitations of AI-Based Pain Assessment

While AI offers significant advancements in pain assessment within physiotherapy, its implementation faces several ethical, technical, financial, and systemic challenges that must be addressed for broader clinical adoption.

1. Ethical and Legal Concerns
AI systems depend on large volumes of sensitive patient data-including facial images, voice recordings, and biometric signals-raising critical issues around informed consent, data ownership, privacy, and security. Passive monitoring technologies, such as facial recognition or sleep tracking, may intrude on patient autonomy, especially among vulnerable populations like children and the elderly. Robust ethical guidelines, transparent data governance, and compliance with regulations such as HIPAA and GDPR are essential to ensure responsible use and build trust [8, 10].

2. Model Bias and Limited Generalizability
AI algorithms are only as unbiased as the data they are trained on. Datasets skewed toward specific demographics-such as certain ages, ethnicities, or genders can cause AI tools to perform poorly in underrepresented groups. For example, facial recognition models trained mainly on adult faces may inaccurately assess pain in paediatric or geriatric patients. This bias risks unequal care and limits AI's applicability across diverse populations and clinical settings. Expanding dataset diversity and validating models in real-world environments remain critical [11].

3. Cost and Accessibility Barriers
AI-based pain assessment often requires expensive technologies like advanced wearables, motion capture systems, and cloud computing, which may be unaffordable for resource-limited clinics, rural centres, or low and middle-income countries. Beyond initial costs, ongoing expenses for software, data storage, and maintenance further challenge accessibility. Without institutional support or affordable solutions, disparities in access to AI tools risk widening.

4. Integration Challenges in Clinical Practice
Effective AI adoption demands infrastructure upgrades, interdisciplinary collaboration, and clinician training. Many physiotherapists may lack digital literacy or confidence in interpreting AI outputs, leading to underuse or misapplication. Additionally, AI tools often lack interoperability with existing electronic health records and hospital systems, complicating workflow integration and increasing administrative burden. Prioritizing user-friendly interfaces, training, and clinical decision support is vital for seamless implementation [8, 11].

5. Regulatory and Validation Hurdles
The regulatory framework for AI in healthcare is still developing. Many AI tools lack formal validation, standardized protocols, or regulatory approval, raising concerns about their safety and reliability. Without robust clinical trials and peer-reviewed evidence, clinicians may hesitate to rely on AI for critical pain assessment and management decisions.

Future Directions

Future advancements in AI-based pain assessment in physiotherapy will enhance tele-rehabilitation by enabling accurate and continuous pain monitoring during remote therapy, improving patient engagement and treatment outcomes beyond traditional clinical settings. The development of multimodal AI systems that integrate facial expressions, vocal cues, kinematic data, and physiological signals will provide more comprehensive and precise pain evaluations. Predictive analytics will further enable forecasting of pain episodes and individual therapy responses, allowing clinicians to implement proactive, personalized interventions. Additionally, AI will synergize with robot-assisted rehabilitation and smart environments, where AI-equipped hospital rooms or homes can passively monitor movement, posture, and vocal stress to detect pain episodes, offering continuous, context-aware support without constant clinician oversight. As AI becomes increasingly embedded in patient care, future designs will emphasize transparent algorithms with interpretable outputs, patient-centered interfaces accessible to all age groups, and robust data security protocols to ensure ethical compliance. These innovations will be crucial to maintaining equity, safety, and widespread acceptance of AI tools in physiotherapy [7, 11].

Conclusion

AI-based pain assessment represents a major advancement in physiotherapy, overcoming the limitations of traditional

subjective methods by leveraging technologies like facial recognition, wearable sensors, biosignal analysis, and predictive modelling. This approach delivers enhanced objectivity, precision, and personalized pain management across diverse patient groups. It empowers physiotherapists to make more informed clinical decisions, tailor treatments to individual needs, and monitor progress with real-time feedback. AI is especially valuable in specialties with communication challenges-such as paediatric, geriatric, neurological, and oncology rehabilitation-promoting compassionate and equitable care for vulnerable populations.

Despite its transformative potential, the integration of AI into routine clinical physiotherapy is not without challenges. Ethical concerns regarding data privacy, model bias, cost of technology, and the need for clinician training and infrastructure development must be systematically addressed. Additionally, robust validation through clinical trials and interdisciplinary collaboration is essential to ensure reliability, safety, and clinical acceptance. Looking forward, the future of AI in physiotherapy lies in multimodal, predictive, and tele-integrated systems that support early intervention, remote monitoring, and long-term recovery. With responsible development and equitable implementation, AI-based pain assessment can contribute to a more responsive, human-centered, and effective rehabilitation ecosystem, ultimately improving patient outcomes and quality of life.

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